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Machinability of Al-Si-Cu cast alloy containing bismuth and antimony when dry turning using coated carbide insert

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**Keywords:** Turning; Aluminum alloy; Melt treatment; Surface roughness; Chip morphology

### Abstract

Surface roughness and cutting force are two key measures that describe machined surface integrity and power requirement evaluation, respectively. This investigation presents the effect of melt treatment with addition of bismuth and antimony on machinability when turning Al-11%Si-2%Cu alloy. The experiments are carried out under oblique dry cutting conditions using a PVD TiN-coated insert at three cutting speeds of 70, 130 and 250m/min, feed rates of 0.05, 0.1, 0.15mm/rev, and 0.05mm constant depth of cut. It was found that the Bi-containing workpiece possess the best surface roughness value and lowest cutting force due to formation of pure Bi which plays an important role as a lubricant in turning process, while Sb-containing workpiece produced the highest cutting force and highest surface roughness value. Additionally, change of

silicon morphology from flake-like to lamellar structure changed value of cutting force and surface roughness during turning.

## 1. Introduction

Aluminum-silicon alloys are increasingly being employed in the aerospace industry, satellite bearing and inertial navigation systems [1]. They are notable materials owing to the fine thermal conductivity, low expansion coefficient and good corrosion resistance. Among Al-Si cast alloys which comprise over 80% of cast aluminum alloys, hypo-eutectic alloy is additionally appealing because of the low material cost and excellent castability [2]. The inherent brittle nature of Si restricts its alloy applications in automotive and aerospace components which is related to mechanical stresses, ductility and high fatigue strength. Therefore, melt treatment with the addition of elements like strontium and sodium is generally used to alter the morphology of Si and meet these requirements [3].

Modification melt treatment in Al-Si cast alloys leads to a change in the morphology of eutectic silicon from coarse brittle flake-like to fine fibrous morphology, resulting in improved mechanical properties [4,5] especially ductility and fatigue life. By the addition of certain elements to the melt prior to solidification, chemical modification can be achieved [6]. Elements such as Na, Sr and Ba show marked effect on the eutectic silicon when added to molten Al-Si alloys by changing its morphology to fibrous appearance. Other elements such as Sb and Yb can refine the silicon morphology and alter its structure into partially modified or lamellar structure [7-9].

It has been reported that antimony (Sb) transforms the morphology of Si from flake to lamellar structure and consequently enhances the mechanical properties [3,10] along with wear resistance [11].

Machovec *et al.* [12] reported a relatively minor effect of Bi addition on the silicon morphology of Al–Si alloys in 319 type aluminium alloy. It was found that the addition of 1 wt. % Bi refines rather than modifies the Si structure and improved tensile strength, elongation and the absorbed energy for fracture of near eutectic Al-Si alloys. Moreover, Bi-refining effect intensified with increasing cooling rate [13].

In terms of machinability, chip breakability evidently improves at higher Si content when turning Al-Si alloy with a carbide cutting tool (K10) at a constant feed rate of 0.1 mm/rev, cutting depth of 0.5 mm and cutting speed between 0.5 and 2m/s [14]. Basavakumar *et al.* [15] noted an improvement in machinability and surface characteristics of Al-Si cast alloy treated with combination of Sr modifier and Al-3Ti-B grain refiner at a constant feed rate of 0.2mm/rev, cutting speed of 26m/min and 0.4mm depth of cut with PVD and polished CVD diamond-coated tools. It has additionally been reported that surface quality enhances when the cutting parameters are optimized [16]. Ibrahim *et al.* [17] were investigated the evaluation of tool wear when machining SiCp-reinforced Al-2014 metal matrix composites (MMCs). They have found that coated cutting tools performed better than uncoated cutting tools in terms of tool wear for all the materials machined. The better performance of them can be attributed to the coating and a larger and more stable built-up-edge (BUE) formation. Temeret *et al.* [18] have been attempted to the Investigation of mechanical and machinability properties of SiC particle reinforced Al-MMC. They have reported that machinability of MMC is very different from traditional materials because of abrasive reinforcement element. This is due to abrasive element causes more wear on

cutting tools. Flank wear of cutting tool are also increased with increase in reinforcement ratio. Reportedly, at greater cutting speeds the cutting temperature rises when machining eutectic and a hypereutectic Al-Si alloy. A linear relationship was identified between them, as primarily attributed to increased heat localization. Surface roughness was found to decrease at higher cutting speeds due to the reduced tendency for build-up-edge formation [19-20]. Irrespective of several papers studied on microstructure and mechanical properties of Al-Si alloy, very few data on the effect of Bi and Sb additions have been found in the literature that extensively address the influence of these elements on machinability characteristics of Al-Si-Cu cast alloy when dry turning. Therefore, having an understanding of these alloys' machinability is imperative when it needs to fabricate of some industrial products which produce by casting process. The aim of this work is to investigate the machinability of Al-Si-Cu alloys containing bismuth and antimony when dry turning using coated carbide inserts. Our findings help in the comparison of the results and afford a better understanding the features of the machinability of Al-Si system.

## 2. Experimental details

A turning investigation was accomplished on Al-11.3Si-2Cu cast alloy with 80-90HV hardness, 125-140MPa yield strength (YS) and 130-160MPa ultimate tensile strength (UTS) using the CNC machine (ALPHA 1350S). Experimental setup (dynamometer) shown in Figure 1. Particulars regarding the cutting tool are given in Table 1. Kennametal inserts with 35° rhomboid geometry with nose radius 0.2 mm and Relief angle ( $\alpha$ ) 5° on a Kennametal holder SVJBL-1616H11 were used. All machining conditions were selected according to the tool maker advice. To fabricate the workpiece a commercial Al-11.3Si-2Cu ingot was melted and prepared using an induction furnace. Pure Bi shots and pure Sb granules at concentrations of 1wt.% Bi and 0.5%

Sb were added to melt according to the optimum concentration for each additive which was determined by computer aided cooling curve thermal analysis (CA-CCTA) and microscopic inspection observed depression in eutectic growth temperature in previous studies cited [21] and the melted materials were stirred to achieve complete homogenization. The molten alloy was then poured at a temperature of  $730 \pm 5^\circ\text{C}$  into the permanent mold. Therefore, three different workpieces with chemical compositions listed in Table 2 were produced. Turning tests were carried out on a CNC machine (ALPHA 1350S) with 8.3kW power drive and 6000rpm maximum spindle speed. The tool was held in a standard “Kennametal” tool holder mounted onto a three-component piezoelectric dynamometer (KISTLER, 9265B, Switzerland). The data acquisition system recorded cutting force ( $F_c$ ) during machining at sampling frequency such that 20 points/cycle could be obtained. Three cutting speeds of 70, 130, 250m/min and feed rates of 0.05, 0.1, 0.15mm/rev were employed respectively, whilst the depth of cut was fixed at 0.5mm. Surface roughness was measured (using a Mitutoyo-Formtracer CS 5000) with accuracy of  $\pm 0.01\mu\text{m}$  and 9.8 mm Cut off Length at different positions on the circumference of the workpiece. The average surface roughness of the recorded values ( $R_a$ ) was calculated and served to investigate workpiece morphology after the machining process. Besides,  $R_a$  values were more common than the  $R_t$  and  $R_z$  values because its consider the averages of peaks and valleys on the surface. In addition, surface roughness was recorded via FESEM (Supra-35VP, Carl Zeiss) and atomic force microscope (AFM) (model SPM- 9500J2) to surface characterization. Metallography samples were prepared (polishing machine and grinding papers with grade of 250,400,800,1200, 2000,2500,4000) following standard grinding procedures.

### 3. Results and Discussion

### 3.1 Surface roughness

Figure 2 provides the surface roughness values at various cutting conditions for Al-11.3Si-2Cu, Bi-containing and Sb-containing alloys. Surface roughness increased when feed rate went from 0.05 to 0.15mm/rev in all machining conditions. Regarding the results obtained and indicated in Figure 2, surface roughness decreased when cutting speed was increased from 70 to 250 m/min. The Bi-containing alloy exhibits the best surface roughness value at just below 1 $\mu$ m at a feed rate of 0.05 mm/rev and cutting speed of 250m/min (Figure 2c). Compared to the base alloy, the Sb-containing alloy has the highest surface roughness value of roughly 6 $\mu$ m at a cutting speed of 70m/min and feed rate of 0.15mm/rev. This may be related to the dominant feed mark and increased distance from peak to valley on the machined surface (Figure 4b, d and f).

It is worth to mention that the temperature on the tool face plays a major role with respect to the size and stability of buildup edge (BUE) formation [22]. Figure 3 demonstrates the built-up edge formation in cutting speed of 250 m/min and feed rate of 0.15 mm/rev in machining of Al-11.3Si-2Cu base alloy and Sb-containing workpieces, respectively. It is clear that massive BUE covered the rake face of the tool in Sb-containing materials in comparison with base alloy which leads to increase surface roughness value in Sb-containing workpiece after machining process.

There is no doubt that higher BUE formation tendency with increase in ductility of Sb-containing workpiece than the base alloy may be related to increase in surface roughness. Therefore, it is clear that the changes in the topography and surface roughness are related to the change in hard phase morphology. It has been reported that Silicon particles were elongated in the Sb-containing workpiece owing to the tearing surface during machining and consequently, the surface roughness value was higher compared to the other workpieces [20].

FESEM images and corresponding feed mark images of the machined subsurface for Al-11.3Si-2Cu, Bi- and Sb-containing workpieces are shown respectively in Figure4 (e-f). It is clear in Figure4 d that the Bi-containing workpiece presented the lowest feed mark variation and best surface roughness of about 2.4  $\mu$ m. However, Sb-containing workpieces had the highest surface roughness value near 4.2 $\mu$ m with the highest feed mark. Moreover, it is obvious that surface tearing in the Sb-containing workpiece was more extensive than in the Bi-containing and base alloy.

From Figure 4, it seems that not only the silicon morphology, but other parameters must also be considered for the bismuth-containing workpiece, which exhibited the lowest surface roughness. It is interesting to note that some bismuth-containing particles were detected under back scattered electron (BSE) as shown in Figure 5. The energy dispersive spectroscopy (EDS) spectra confirmed that these particles mainly consist of bismuth. There is some strong evidence that bismuth compounds can partially melt during turning, becoming effective chip-breakers [14]. Thus, it seems that bismuth acts as lubricant due to its low melting point, thereby decreasing the friction between chip and tool edge which leads to lower cutting forces, a low tendency to form BUE, and a smooth surface finish [8].

### 3.2 Cutting force

Cutting forces depend on both the material properties and machinability parameters. It has been noted that cutting forces also depend on coefficient friction between the tool and the material. Therefore they are promoting the rising of built-up edge (BUE) on the rake face of the tools which lead to an increase of the cutting force [23]. Figure 6 illustrates the cutting force ( $F_c$ ) between the base alloy and Bi- and Sb- containing workpieces. Bi-containing alloys presented the lowest cutting force of around 20N at a cutting speed of 250 m/min and feed rate of 0.05 mm/rev and depth of cut 0.5 mm

It has been noted that cutting force decrease by reduction of tool wear and minimizing the BUE formation on the rake of cutting tools [23]. It is clear that Bi had a positive effect on machining of Al-11.3Si-2Cu alloy, which may cause reducing of BUE and diminishing of chip thickness resulting in lower cutting force (figure 7d). Therefore, Bi can act as lubricant during machining process in order to decrease cutting force. On the other hand, Sb-containing alloy showed the highest cutting force near 80 N at a cutting speed of 70 m/min and feed rate of 0.15 mm/rev. As can be seen, Sb-containing has increased the cutting force because of the massive BUE on the rake of cutting edge and longer chip during turning (figure 7f). Moreover, cutting force clearly



increased when feed rate increased from 0.05 to 0.15 mm/rev and it decreased when cutting speed went up from 70 to 250 m/min.

### 3.3 Chip formation and chip adhesion

Chip formation and the corresponding adhesion of chips onto the flank of tools at a cutting speed of 250 m/min and feed rate of 0.05 mm/rev are shown in Figure 7. The types of chips formed vary, which may be attributed to the material properties and cutting parameters [24]. The interface frictional conditions cause the tool-chip contact to lead to the deformation and curling-away of the chips from the tool-rake face. Since chip formation influences tool design, it is crucial to consider tool material and cutting parameter selection in machining [25]. It has been reported that the presence of Si and Al<sub>2</sub>Cu in alloy amplifies chip breakability which occurs more so in wet cutting than in dry cutting. Moreover, fractures in the second phase of turning intensify chip breakability during turning [25].

It is clear that the type of Si shape (flake or lamellar shape) has a major effect but cutting speed slightly affects chip shape (figure 7 a, c and e). The chips formed during base alloy workpiece machining in cutting speed of 250 m/min and feed rate of 0.15 mm/rev are long, while Bi-containing workpieces exhibit chip disposability and shorter chips in the same condition. Also, cracking of some addition particles during turning could be attributed to the enhanced chip breakability of Al-11.3Si-2Cu alloy. However, chip formed for Sb-containing workpieces were longer than others, it was less breakable and free from the formation of cracks.

Short chips are commonly desired to obtain undamaged surface [26] that can translate to better surface roughness and machinability. Chip adhesion on the rake face of the tools and workpiece chip shapes at a cutting speed of 250m/min and feed rate of 0.05mm/rev are shown in Figure 7 (b,

d and f). Because, in spite of increasing the cutting speed, stuck BUE parts were found on the rake face of the tools, hence cracks were seen on the surface of the machining sample. However, at high cutting speed, the depth of crack was shallow and the distance between the cracks was far from each other. Thus, it can be said that, the formation of small size of BUE at high cutting speed reduce the amount of defects on the machine surface. In contrast to the base alloy workpiece, adding Bi improves workpiece surface roughness by decreasing adhesion on the cutting tools. However, it is evident that Sb increases surface roughness by adding amount of BUE on the rake face of the tools during machining process (figure 7f). Plastic deformation of the soft phase in the cutting zone and buildup at the cutting tool edge are pronounced and the tool geometry changes are noticeable through an increase in surface roughness [27].

### 3.4 Optical and atomic force microscopy

The optical microstructures and AFM images following machining at a cutting speed of 250 m/min and feed rate of 0.05m/rev are shown in Figure8. It is clear that the eutectic Si (gray) in the base alloy with large flake-like morphology (Figure 8a) embedded in the Al matrix (white).The eutectic Si morphology after adding Bi is illustrated in Figure 8 c where the large plate-like Si changes into lamellar or refined shapes, similar to previous reports [12,28]. Moreover, the addition of Sb exhibits a similar effect to Bi addition, as seen in Figure 8 e. In view of the three-dimensional images, hillocks and valleys are observed. Evidently the Bi-containing workpiece displays the lowest surface roughness value through the hillocks in the 3-D dimensional image, while the Sb content is at the highest value of surface roughness as seen in the highest hillocks from the 3-D image. It was observed that adding Bi and Sb has a profound influence on the microstructures of the workpiece cast alloys. Therefore, it can be deduced that

the changes in topography and surface roughness are associated to the morphology changes of the silicon hard phase in the aluminum soft matrix.

It is worth mentioning that although the addition of Bi and Sb produced similar effects on Si morphology as well as refined it, the surface roughness, cutting force and topographical microscopy results for these additions are different. In cases in which Bi is present, a Bi-containing inter metallic may form, which acts as a chip breaker that reduces chip length during machining (Figure7c).

#### 4. Conclusion

The following conclusions were drawn from this study on dry turning of Al-11.3Si-2Cu, Bi- and Sb-containing alloys at three different cutting speeds and feed rates.

- 1- The change of flake-like eutectic silicon into the refined lamellar structure increased surface roughness and decreased machinability of Al-12Si-2Cu cast alloy. However, formation of Bi compound which acts as lubricant during turning can be more likely a reason to obtain the best surface roughness and lowest main cutting force value compared to the base and Sb-containing workpieces.
- 2- Chip formed for Sb-containing workpieces were longer than other workpieces, it was less breakable and free from the formation of cracks. It can be related to massive amount of BUE on the rake face of tools, lead to an increase in value of cutting force and surface roughness.
- 3- Bismuth addition improves machinability of Al-12Si-2Cu cast alloy. This addition is suitable alloying element to add into the aluminum alloys in order to fabricate casting

components with good mechanical properties and machinability which are usually used in automotive industry.

### Acknowledgment

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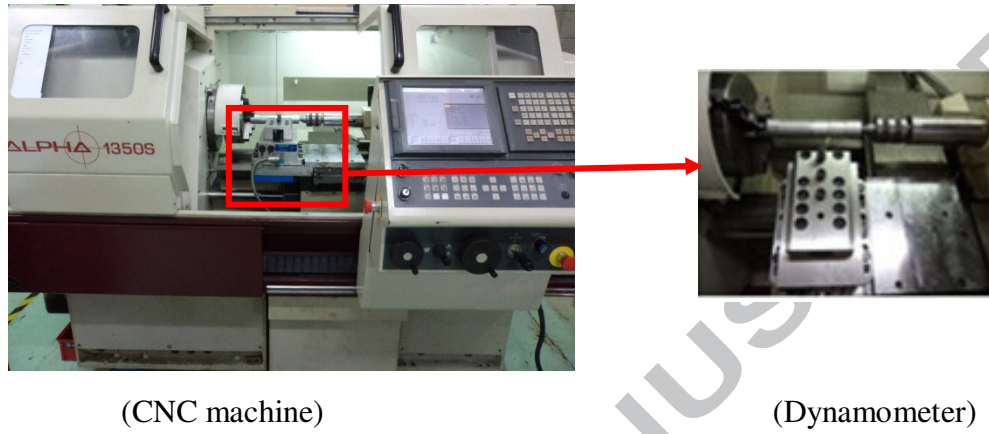


Figure 1. Experimental set up

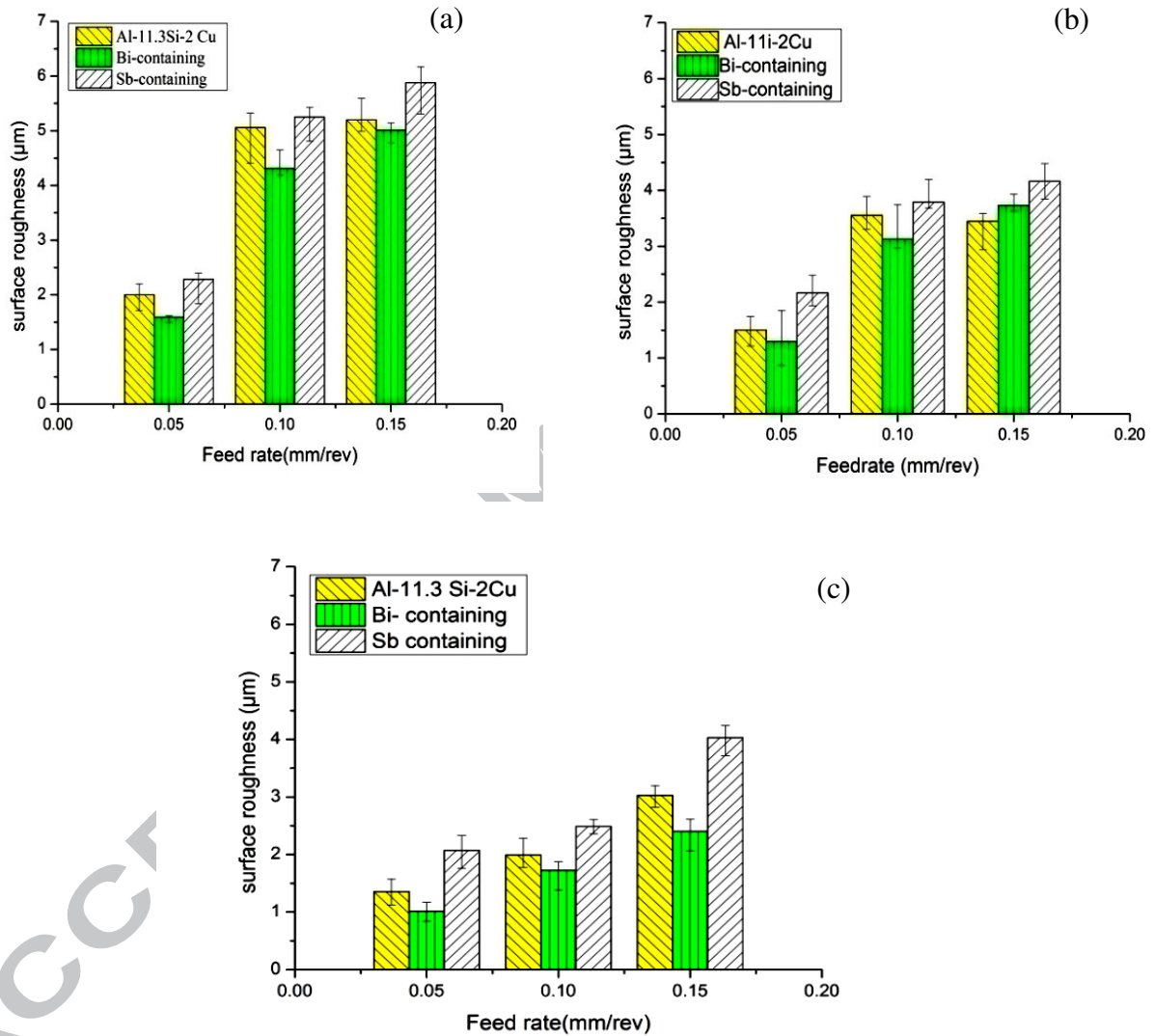


Figure 2. Surface roughness (Ra) comparison of workpieces as a function of feed rates at depth of cut 0.5 mm and three cutting speeds: (a) 70 m/min, (b) 130 m/min, and (c) 250 m/min



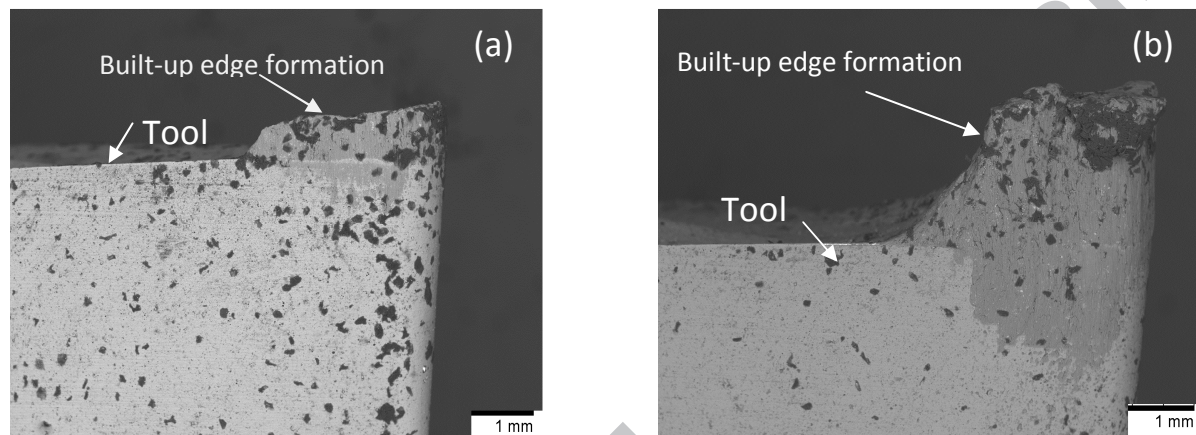


Figure 3. SEM micrographs of Built-up edge formation during turning process at cutting speed 250 m/min, feed rate 0.15 mm/rev and depth of cut 0.5 mm (a) base alloy and (b) adding Sb-containing

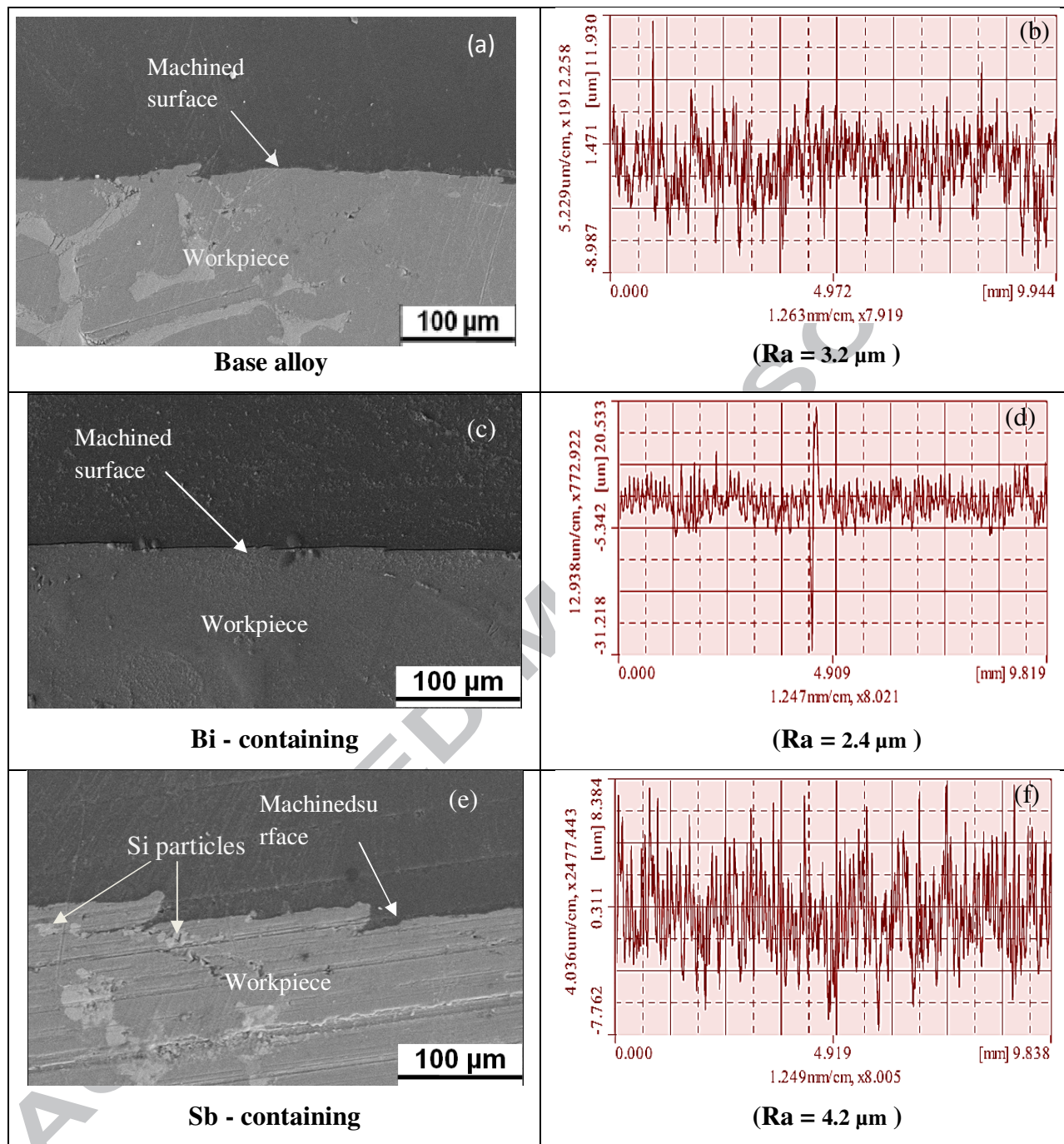


Figure 4. FESEM micrographs and feed mark images of machined subsurface at feed rate of 0.15 mm/rev, cutting speed of 250m/min and depth of cut 0.5 mm (a,b) base alloy, (c,d) Bi-and (e,f) Sb-containing workpieces.

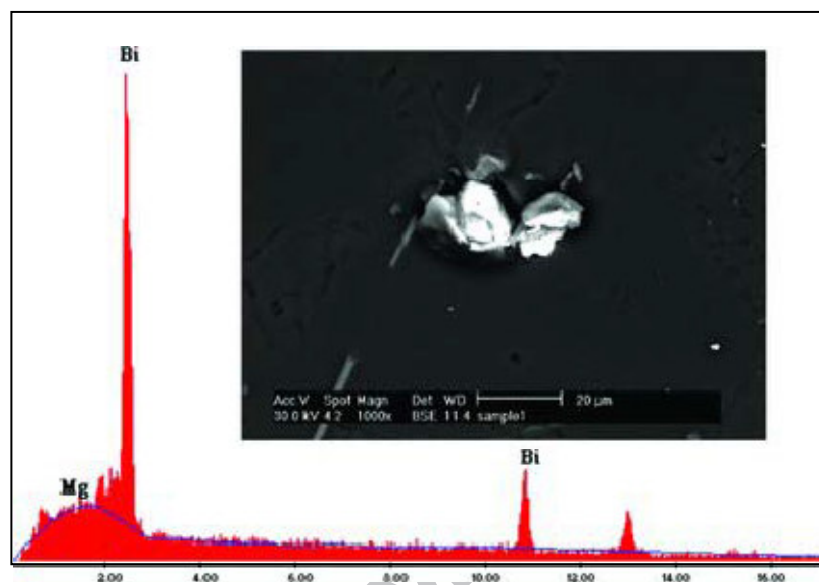


Figure 5. BSE image and EDS spectra of Bi-containing particle (white area)

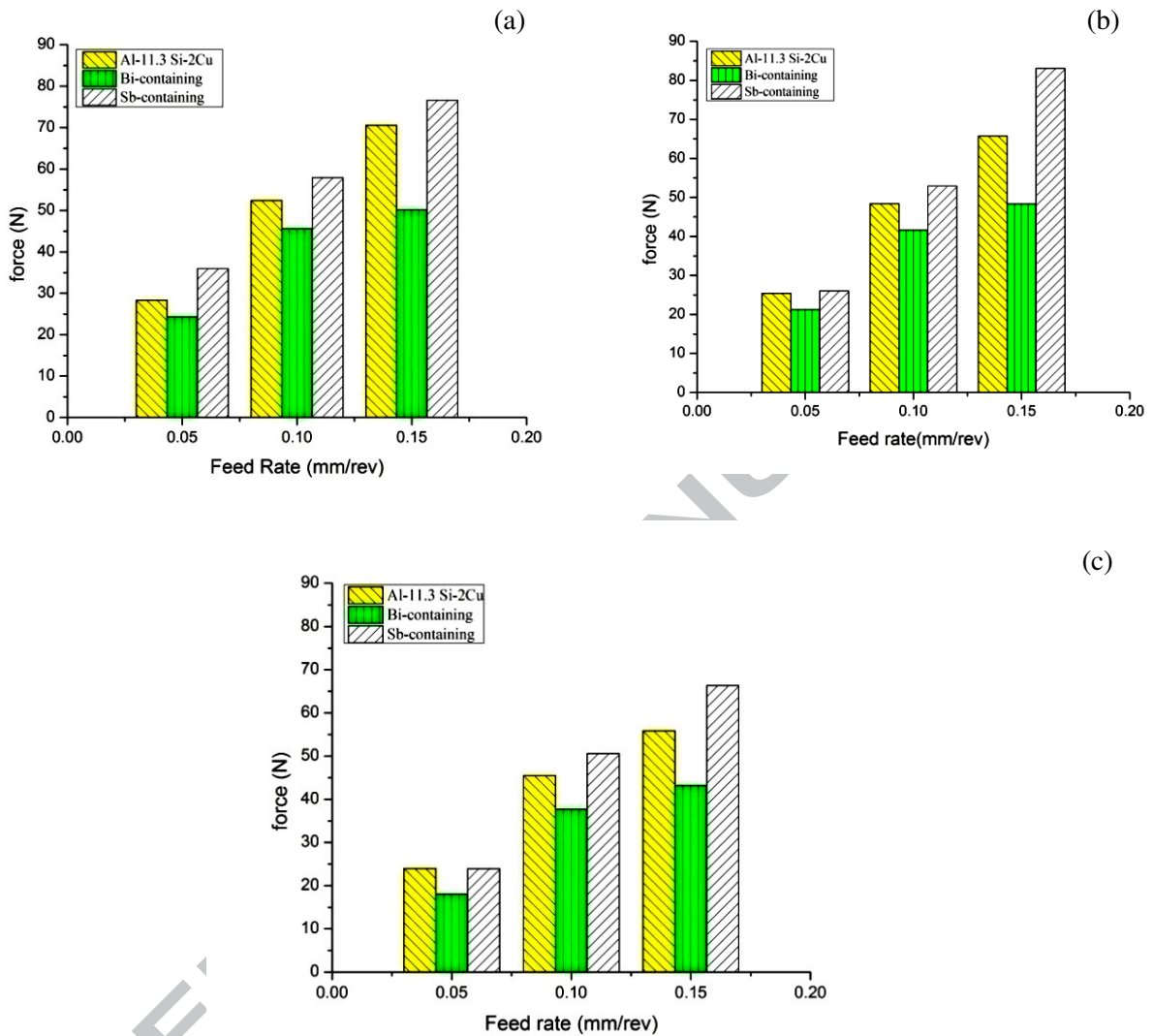


Figure 6. Effect of additives and parameters of machining on cutting force ( $F_c$ ) at depth of cut 0.5 mm and three cutting speeds: (a) 70 m/min, (b) 130 m/min, (c) 250 m/min.

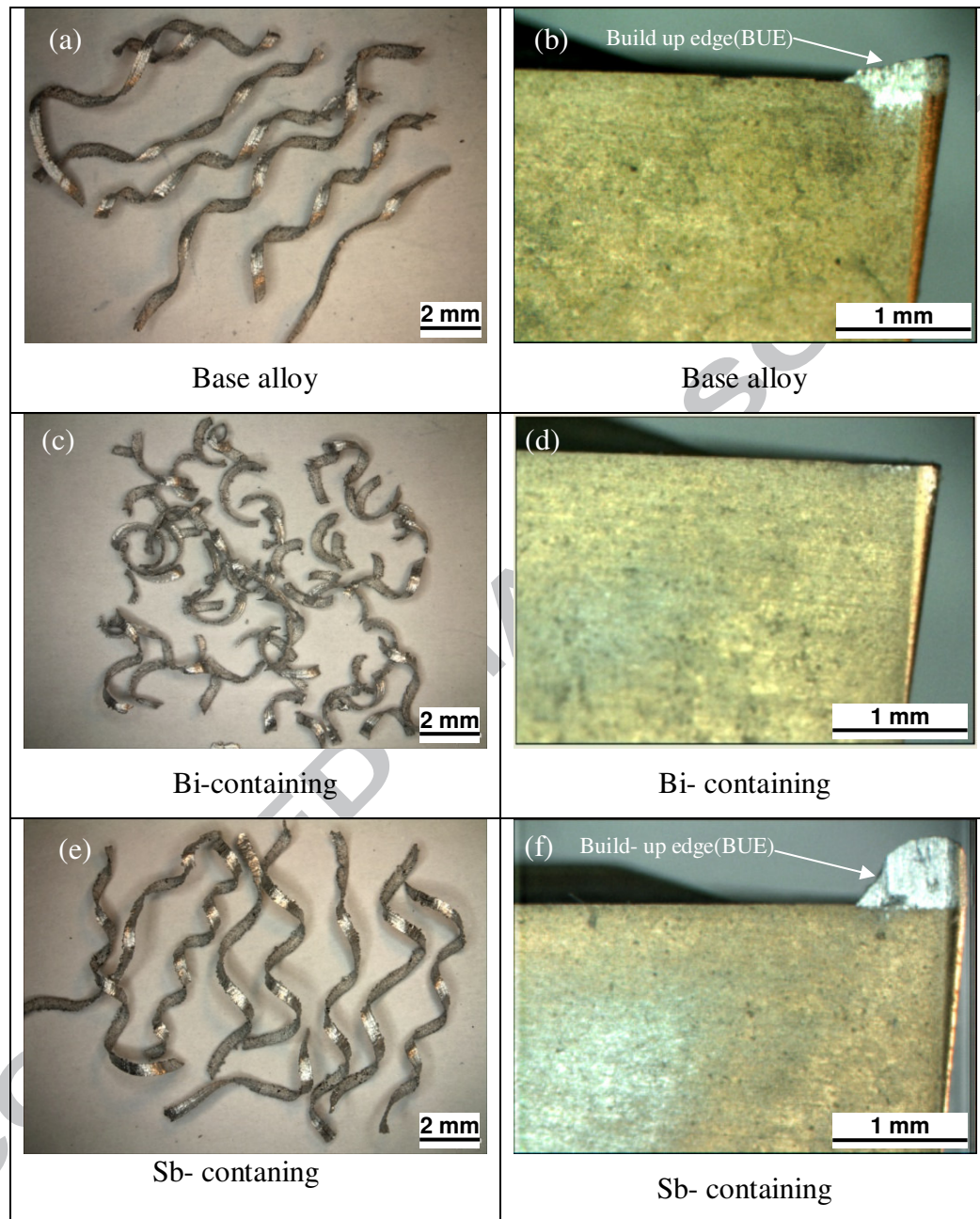


Figure 7. Chip shapes and optical images of flank faces of tools at speed of 250 m/min and feed rate of 0.15 mm/rev and depth of cut 0.5 mm: (a,b) base alloy, (c,d) Bi- and (e,f) Sb-containing alloys.

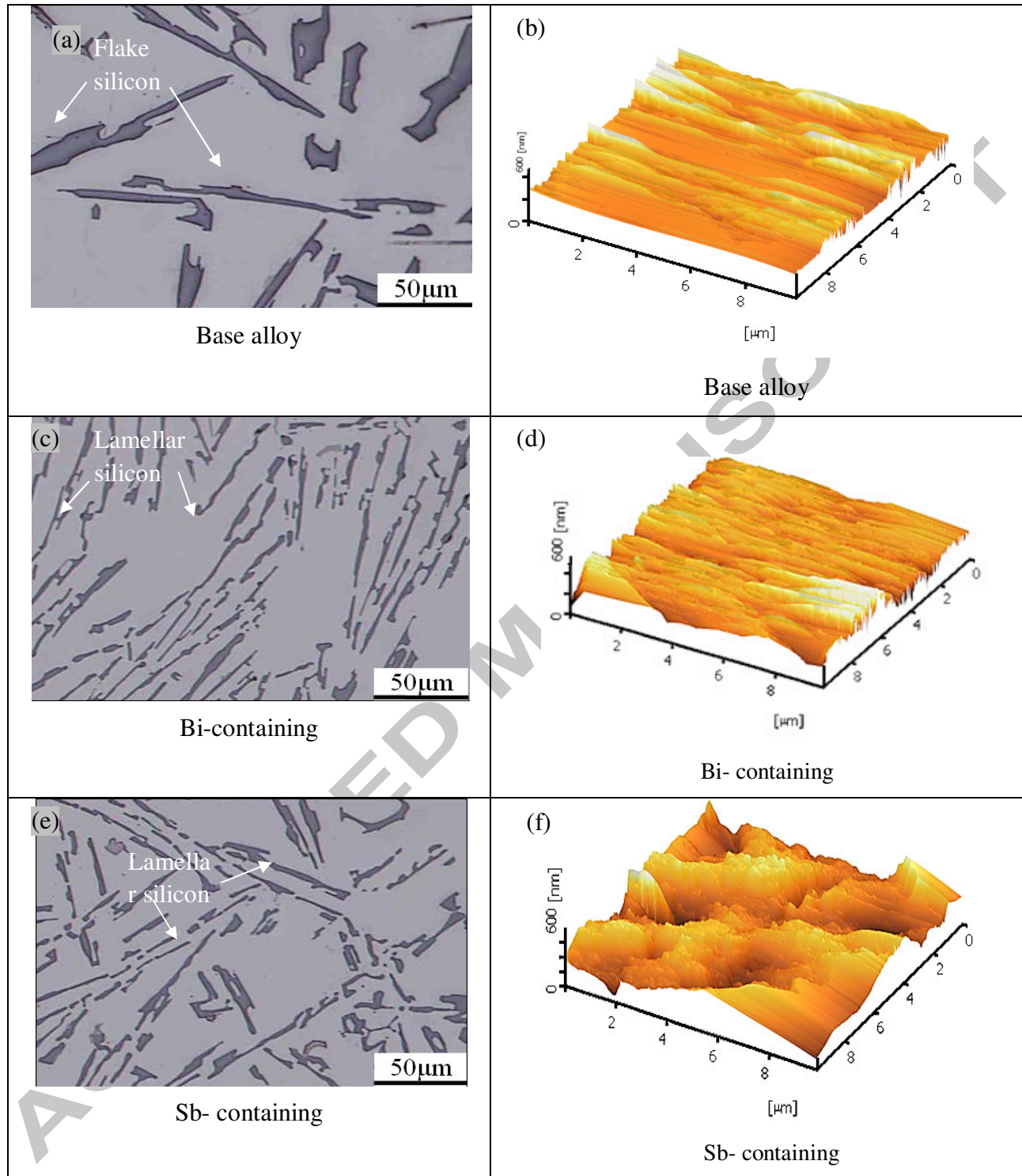


Figure 8. Optical microstructures and atomic force microscopy topographical of machined surface of workpieces in cutting speed of 250m/min, feed rate of 0.05mm/rev and depth of cut 0.5 mm (a, b) base alloy, (c, d) Bi-containing and (e, f) Sb-containing.

*Table 1 Details of the cutting tool*

Tools/Grade	Coating Composition	Process Type	ISO catalog number
KU10	TiN	PVD	VBGT110302F

*Table 2 Chemical compositions of the fabricated workpieces (wt. %)*

Element	Si	Cu	Zn	Fe	Mn	Mg	Ni	Cr	Bi	Sb	Sr	Al
Base alloy	11.3	1.99	0.82	0.35	0.33	0.27	0.06	0.036	-	-	-	Bal.
Bi-containing	11.2	1.65	0.82	0.41	0.35	0.28	0.04	0.032	0.85	-	-	Bal.
Sb-containing	11.3	1.82	0.80	0.43	0.31	0.25	0.06	0.030	-	0.42	-	Bal.

**Highlight**

- 1- Change of silicon shape decreased machinability of Al-12Si-2Cu cast alloy.
- 2- Bismuth addition improves machinability of Al-12Si-2Cu cast alloy.
- 3- Antimony addition increases surface roughness by adding amount of BUE.

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